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Descending into the “snowball”: Improving interpretations of Tonian–Cryogenian palaeoenvironments with sedimentology and multiproxy geochemistry

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The Tonian–Cryogenian transition represents a period of significant physiochemical change in Earth history. It involved variations in oceanic and atmospheric oxygenation, significant changes in the biosphere, tectonic reorganisation, and the onset of the global 'Sturtian' glaciation. Tonian and Cryogenian sedimentary rocks in South Australia represent some of the most well-exposed, continuous and thick sections of this interval globally, recording major environmental shifts through distinct variations in lithology and isotope chemistry. Although this transition is geologically significant, it remains enigmatic due to a distinct lack of comprehensive, contemporary Tonian–Cryogenian research in South Australia.

We present robust palaeoenvironmental interpretations for a complete pre- to post- Sturtian glacial succession in the northern Flinders Ranges. During fieldwork, a ~3km sedimentary log was measured for facies and sequence stratigraphic analyses, and 350 samples were collected for elemental and isotopic geochemical analyses. Our study reveals a pre-glacial succession of river-dominated deltaic sands, which transition to lagoonal platform carbonates. These are unconformably overlain by ice-proximal diamictites and proglacial mudstone with dropstones, consistent with a glaciomarine setting. The post-glacial formation comprises subtidal shales and carbonates, reflecting widespread transgression after the glaciation.

Elemental chemistry, along with C- and Sr-isotope signatures were analysed to determine the primary basin water chemistry, and further constrain the depositional setting. The REE patterns from Tonian carbonate samples indicate low Y/Ho, slight light rare earth element (LREE) depletion, weak negative Ce/Ce* and high Eu/Eu*. This suggests a nearshore, dysoxic setting fed by anoxic deep waters and more oxic shallow waters. Furthermore, there is an inverse trend between $\delta^{13}C$ (7.37‰-(-6.68‰)) and $^{87}Sr/^{86}Sr$ (0.7088-0.7182) values, along with light $\delta^{88}Sr$ values (≤0.211‰). This could reflect a drop in relative sea level and shift to more restricted conditions with sufficient continental input through the Tonian. The Cryogenian carbonate samples record increased Y/Ho, moderate LREE depletion, slight negative Ce/Ce* and low Eu/Eu*, which represents a significant geochemical shift to a more open, oxic to suboxic subtidal environment. This high-resolution study presents new palaeoenvironmental insights into a key Tonian–Cryogenian succession, which sheds light in our understanding of how the world descended into one of the most extreme glaciations ever recorded.